Lattice QCD

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Caveats

- Lattice field theory is very active so there is not enough time to review everything. I made selections based on my interests.
- Not covered
  - High Temperature QCD
  - Nucleon Structure
  - Nonperturbative study of dynamical symmetry breaking
- Many sources of recent reviews cover additional material
  - Lattice 2010: Del Debbio, Heitger, Herdoiza, Hoelbling, Laiho
  - CKM2010: Shigemitsu
  - ICHEP2010: Della Morte, Gamiz, Scholz
  - Charm 2010: Na
- I will borrow (shamelessly).

Background

Basic Methodology

- Lattice QCD uses importance sampling of Euclidian path integral
- Calculation requires an ensemble of correctly weighted gauge field configurations
- Larger ensembles allow smaller statistical errors
- Many physics projects can be done with an archived ensemble
- Must discretize the theory to place on space-time grid
- Groups use actions with different discretizations, but should have same continuum limit

Control of Systematic Errors

- To generate an ensemble we must select certain physical parameters:
  - lattice spacing (a) or gauge coupling (β)
  - grid size ($N_s^3 \times N_t$)
  - sea quark masses ($m_{u,d}$, m_s , m_c)
- To control systematic error we must:
  - take continuum limit
  - take infinite volume limit
  - extrapolate in light quark mass; can use physical *s, c* quark masses

2+1(+1) Ensembles

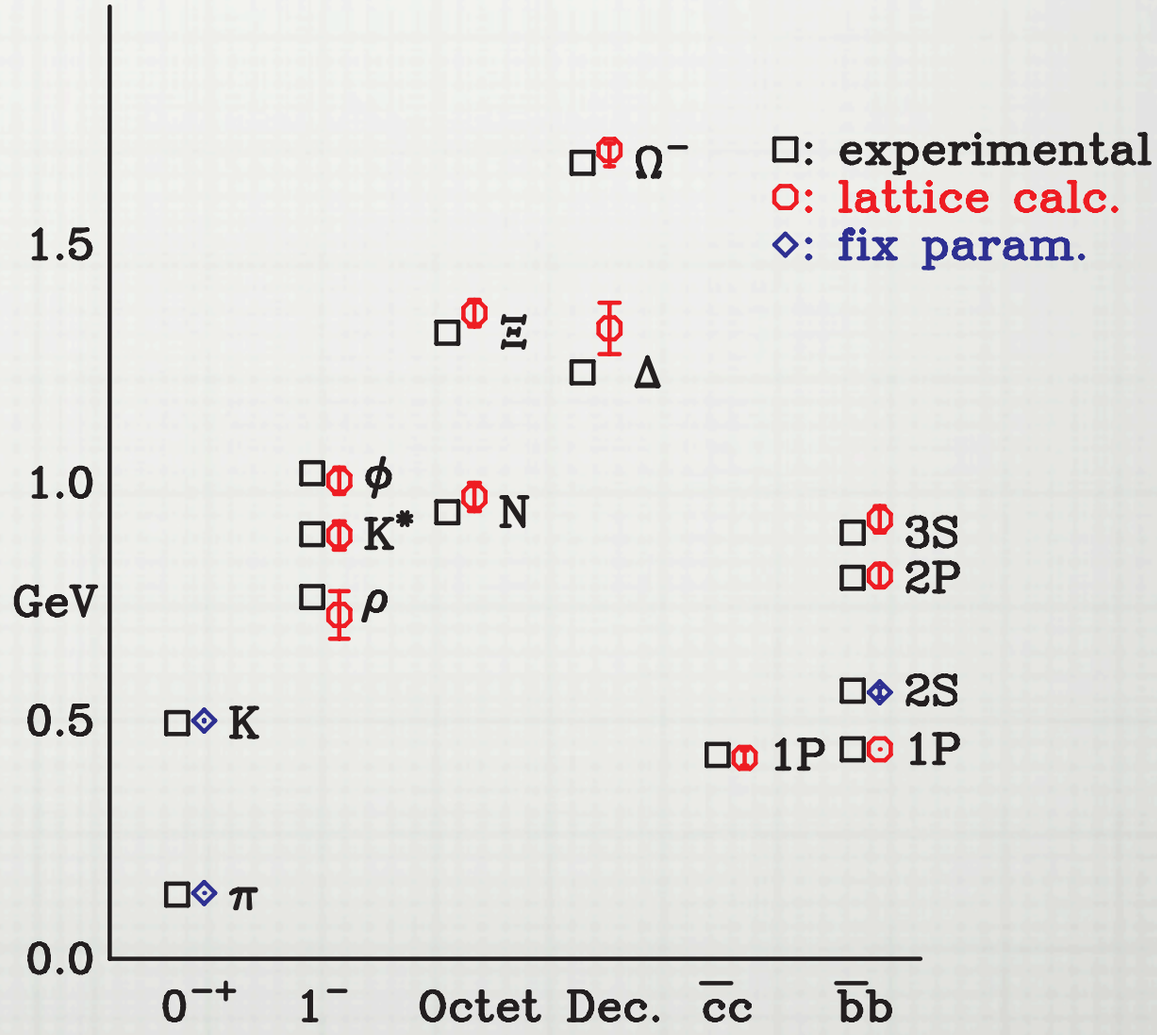
- BMW: Symanzik/Clover, 3-5 lattice spacings
- JLQCD: Iwasaki/Overlap, a=0.11 fm (fixed topology)
- MILC: Symanzik/asqtad, 6 lattice spacings
- PACS-CS: Iwasaki/Clover, a=0.09 fm
- QCDSF: Symanzik/SLiNC, a=0.06 fm
- RBC/UKQCD: Iwasaki/DomainWall, 3 lattice spacings
- ETMC: Iwasaki/TwistedMass, 3 lattice spacings
- MILC: Symanzik/HISQ, 3+ lattice spacings

Results

- I will summarize selected results on
  - spectrum
  - quark masses
  - weak matrix elements
    - decay constants
    - semileptonic form factors
- See RMP **82**, 1349 (2010) for results and references.
- See reviews mentioned earlier for many additional quantities and details

Summary of Hadron Spectrum 1

- Summary of continuum limit of asqtad spectrum results.
- States marked with diamond used to set quark mass or lattice spacing.
- For onium plot difference from spin averaged 1S mass.
- Details in RMP (2010), PDG (2008)



Quark Masses

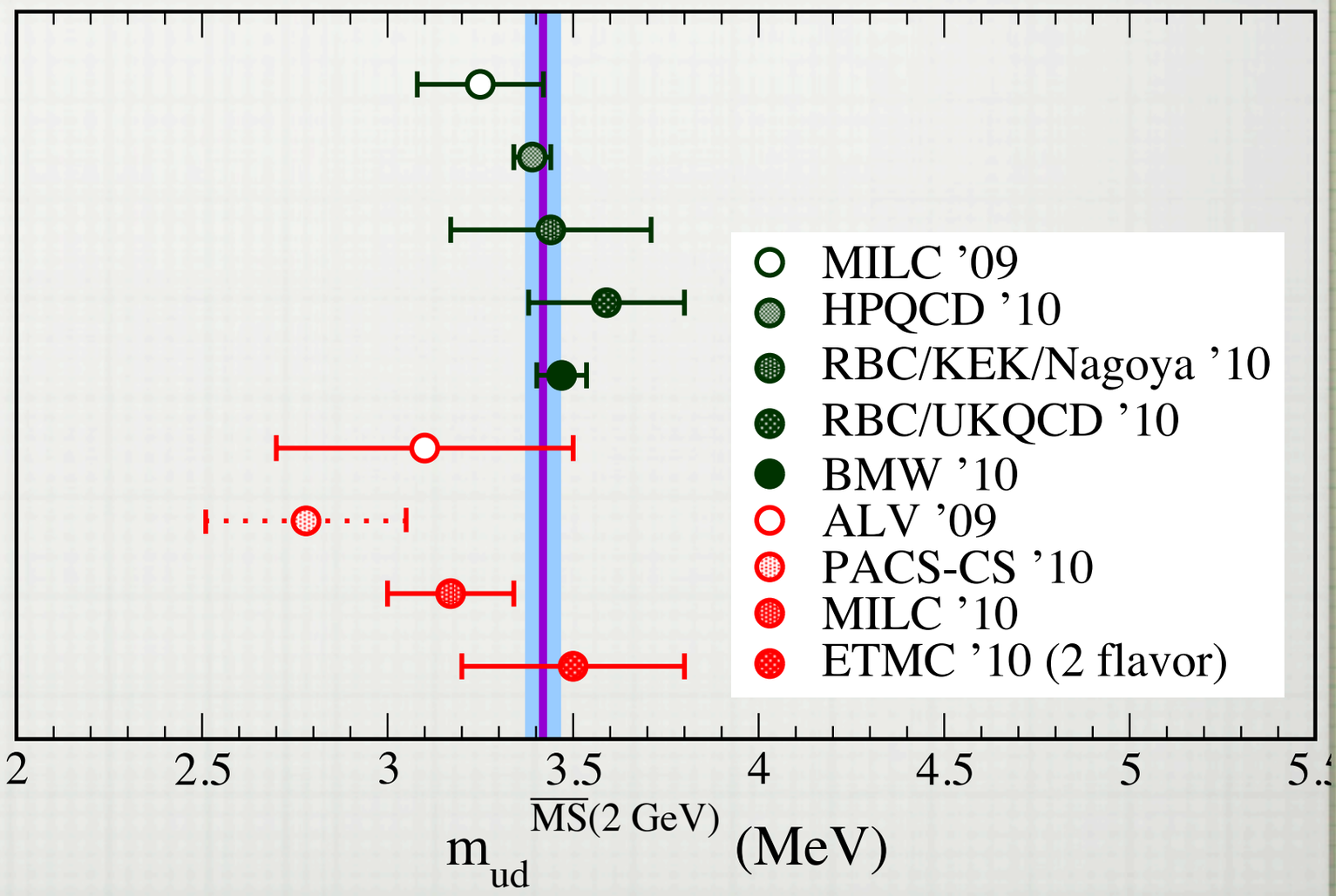
- MILC and MILC/HPQCD reported first 2+1 flavor results in 2004
- HPQCD subsequently produced 2-loop renormalization constant and developed a novel technique of comparing 2-pt functions with continuum perturbative results
- A number of groups with different actions have results to be compared
- Electromagnetic effects are getting increased attention (RBC/KEK/Nagoya, MILC, BMW)
- Nicely summarized by Laiho at Lattice 2010

Lattice Averages

- Laiho, Lunghi and Van de Water: PRD81 034503 (2010) [arXiv: 0910.2928] produced lattice averages for a number of quantities important for extracting Standard Model parameters.
  - www.latticeaverages.org
- FlaviaNet: a group that has been doing this for a while
  - http://ific.uv.es/flavianet/
- PDG: sometimes creates averages of lattice results
- Next four graphs (updated since Lattice 2010) are from Laiho, Lunghi, Van de Water

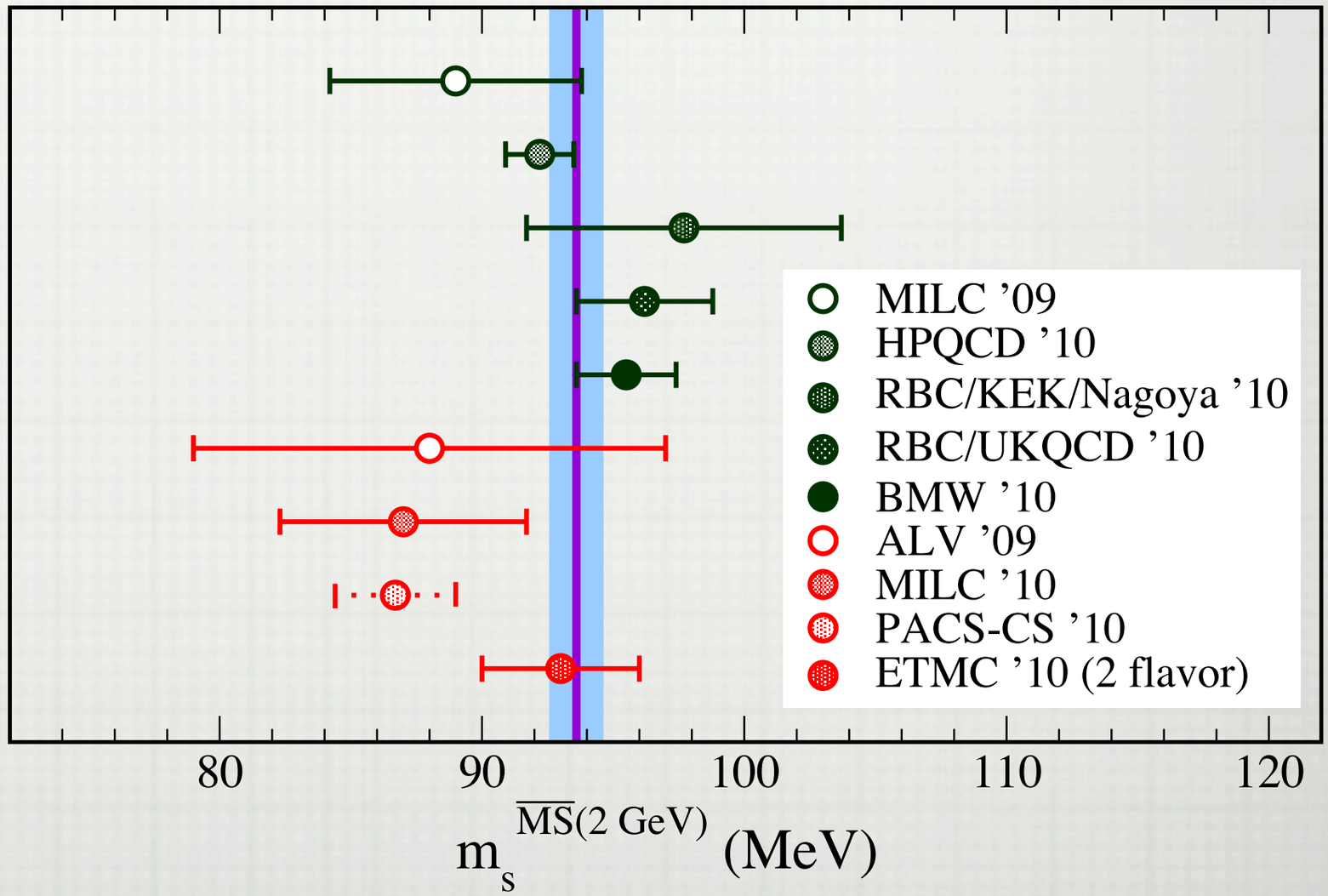
Light quark mass

- values in green included in average result
- average is cyan band
- red results are newer and may include 2 flavor results
- dotted errors don't include full systematics



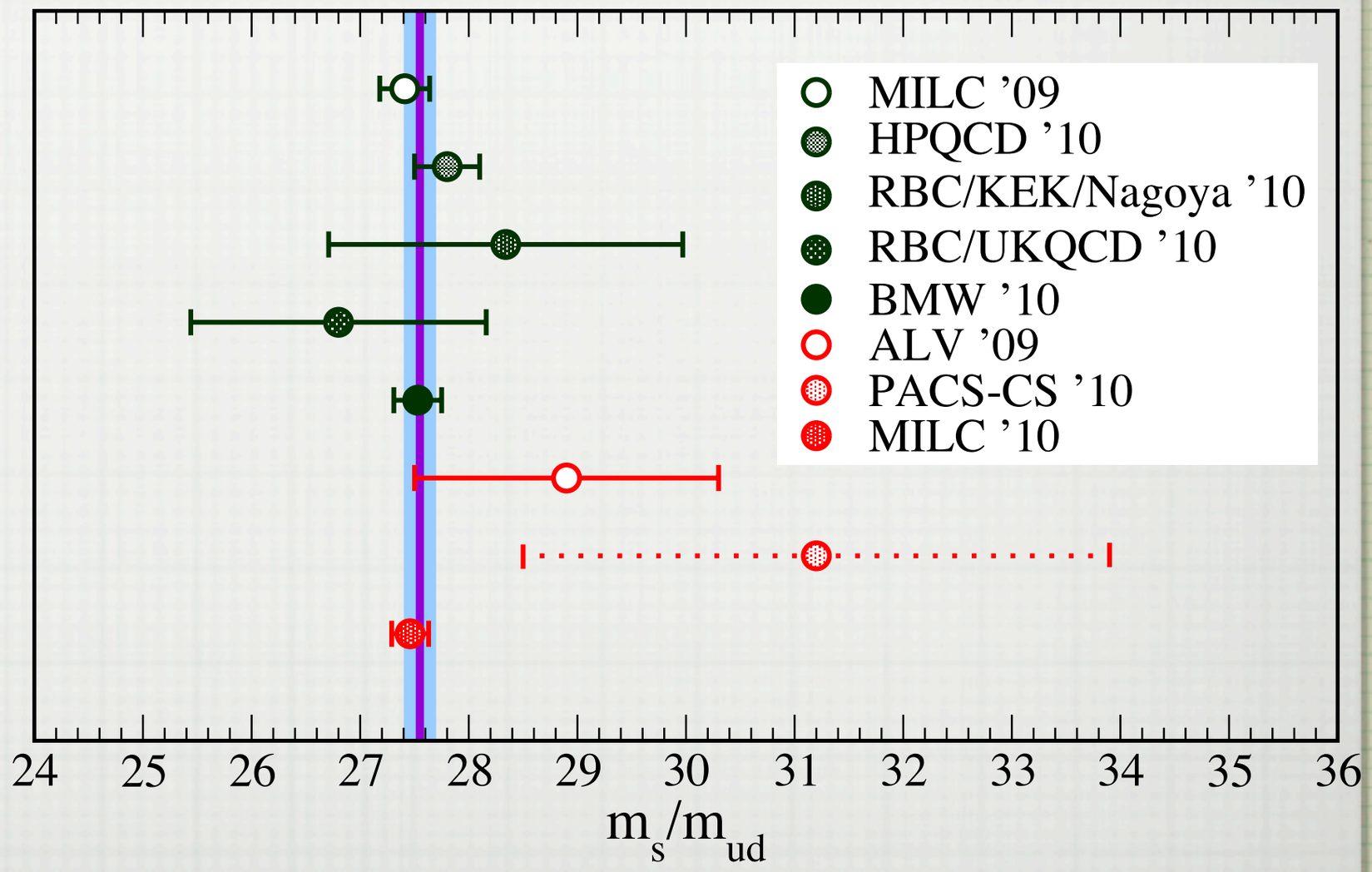
Strange quark mass

- RBC/KEK/Nagoya results include quenched QED and use two volumes on one lattice spacing



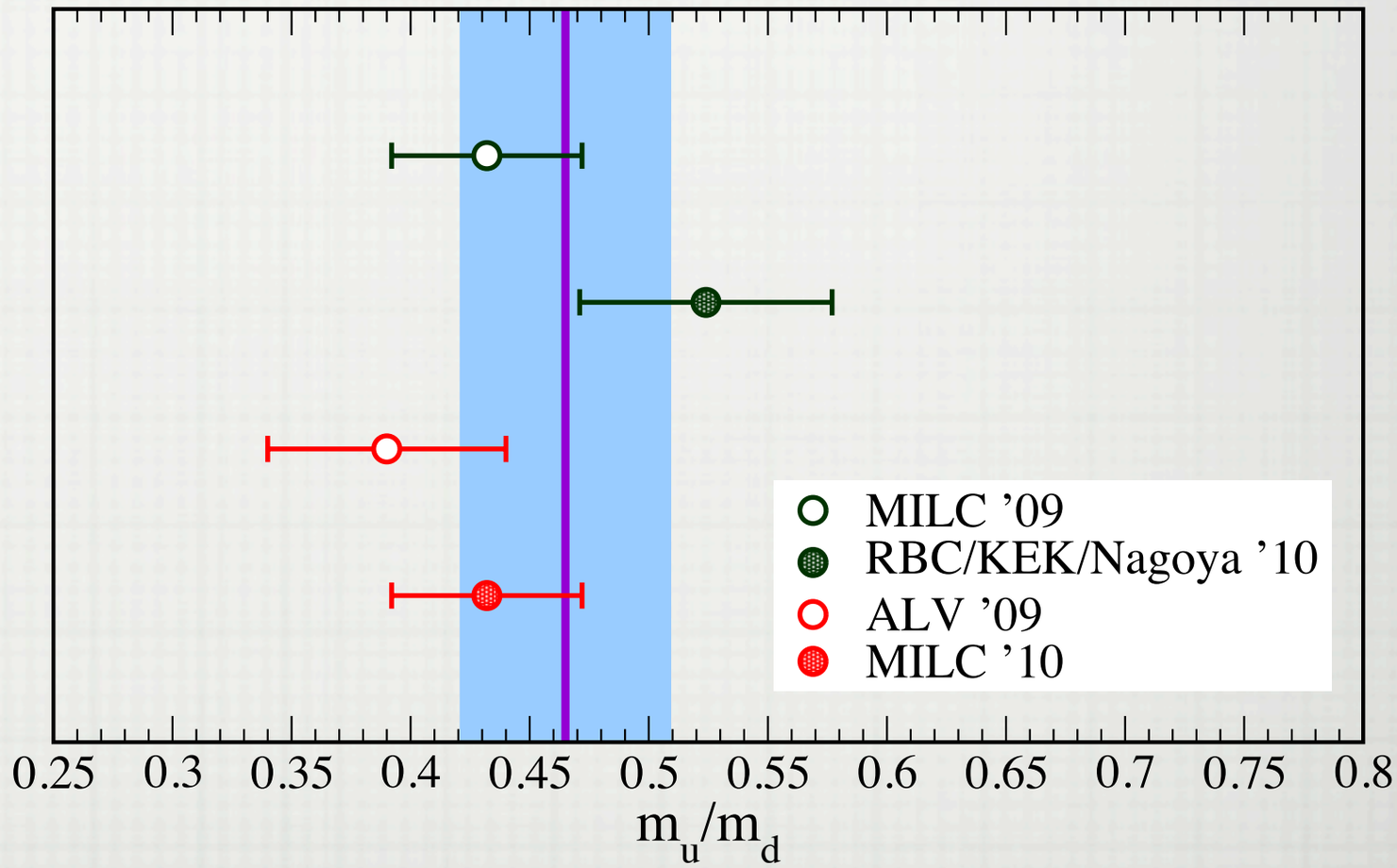
Strange to light mass ratio

- PACS-CS results seem to vary from others, but there is no continuum extrapolation or correction for finite volume effects.
- Their volume is relatively small.



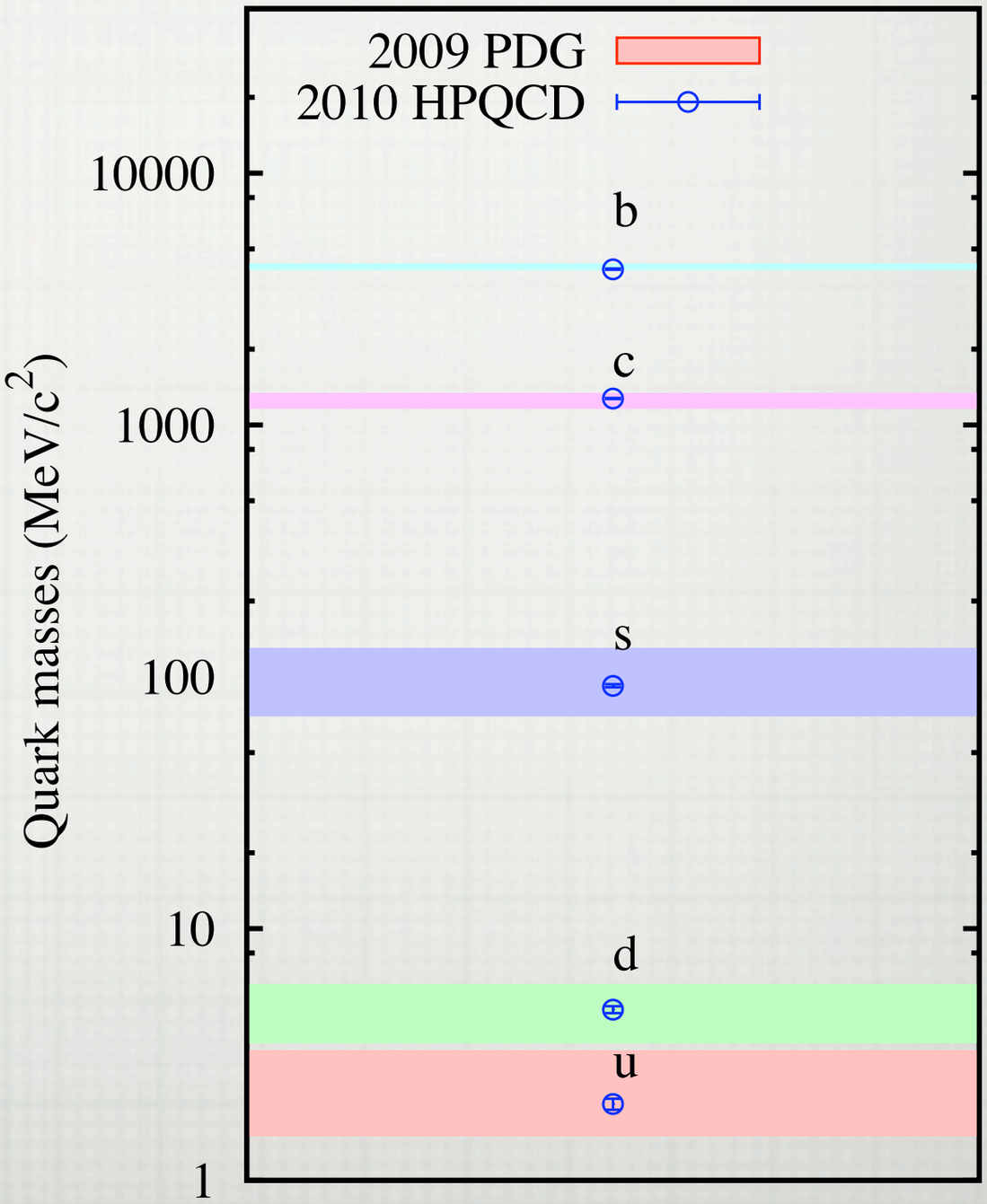
Up to down mass ratio

- This rules out vanishing *u* quark mass as solution to strong CP problem.
- BMW: arXiv:1011.2403 results were available for previous quantities
- Their result for ratio ≈0.449, but not quoted in paper, so don't know error.



HPQCD's quark masses

- HPQCD results using MILC configurations
- Based on moments of 2pt correlators and high order continuum perturbation theory
- arXiv:1004.4285



Weak Matrix Elements

- For extraction of CKM matrix elements from experimental results lack of knowledge of hadronic matrix element often limits precision of matrix element.

- Lattice QCD provides a way to calculate leptonic decay constants and semi-leptonic form factors, and it is essential to produce high precision, reliable results.

- Precision flavor physics is a powerful way to study BSM physics.

  - see Buras: arXiv:1012.1447 for a pedagogic discussion

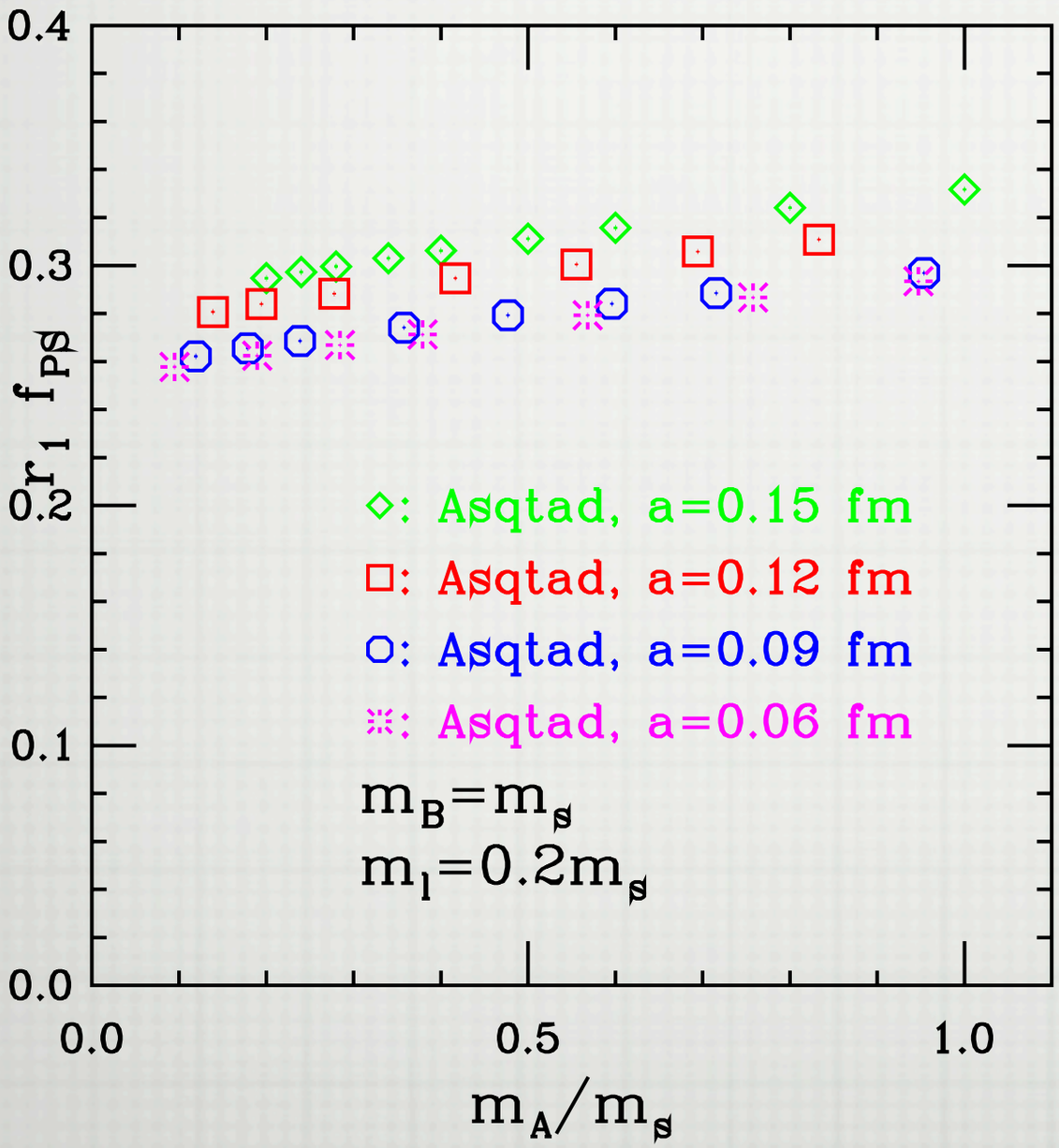
- Time is short, so we only look at a few results

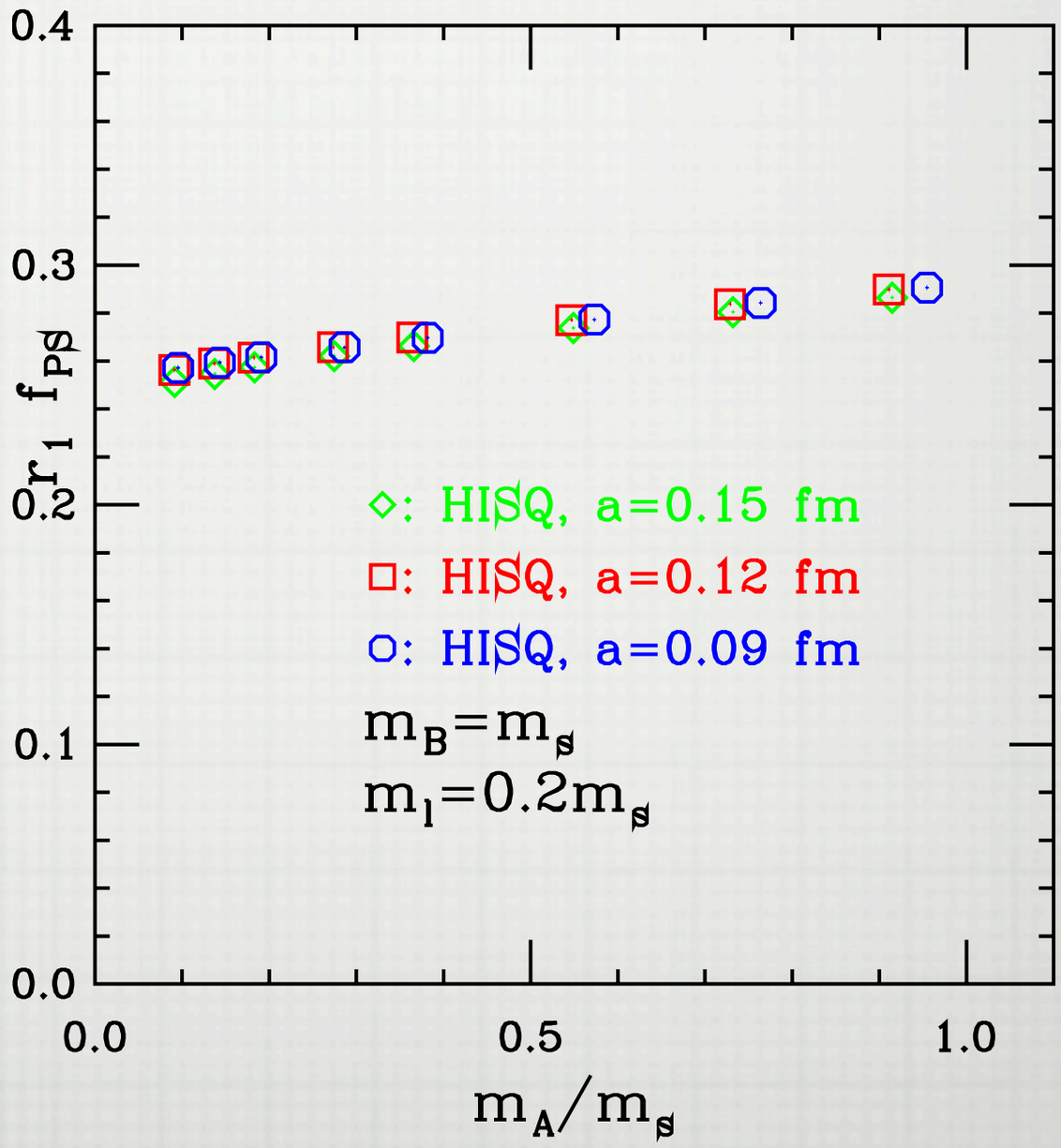
  - see Della Morte, Gamiz, Heitger, Shigemitsu, Na, ...

Relevant Decays

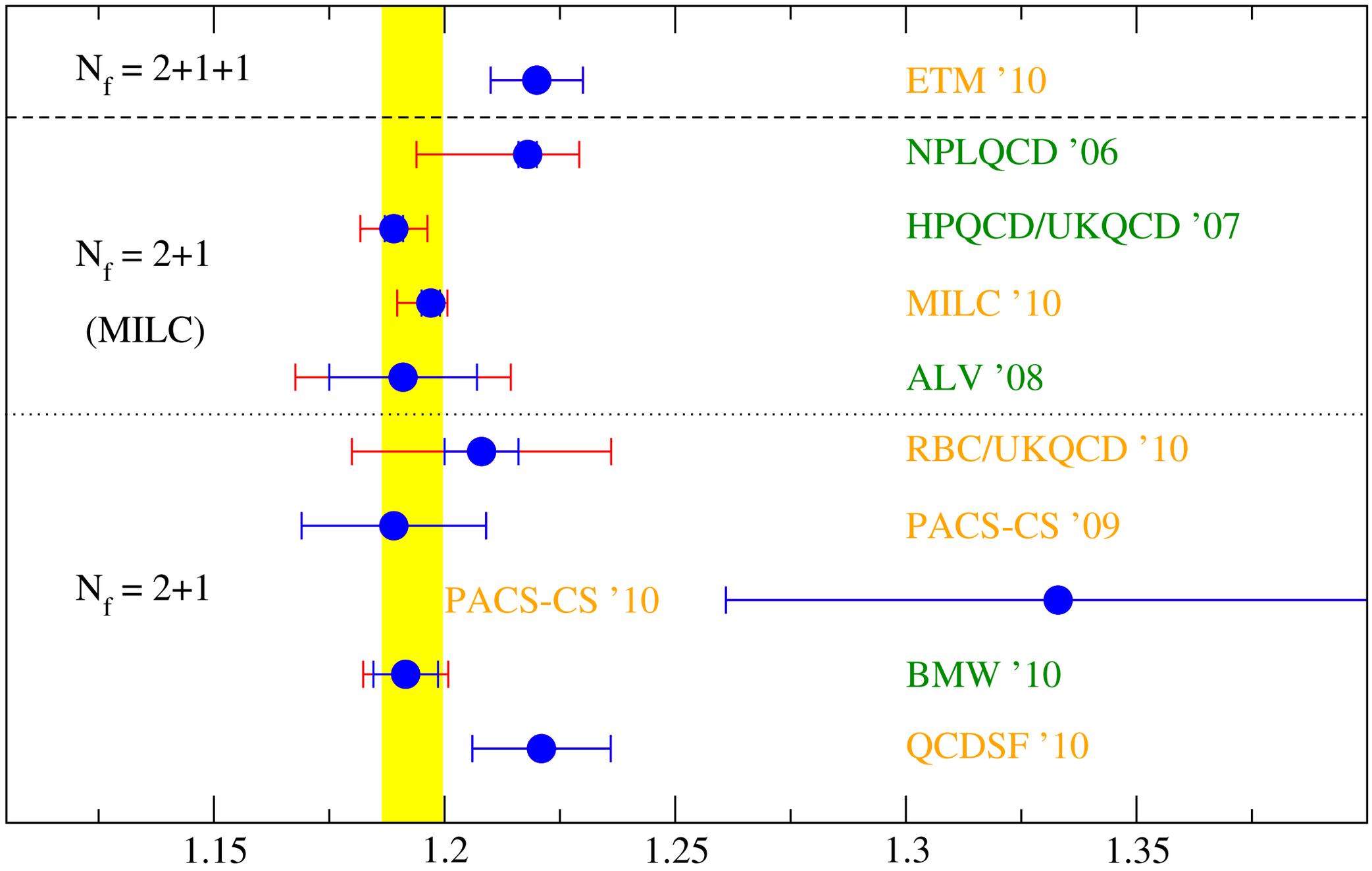
$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to l\nu & K \to \pi l\nu & B \to \pi l\nu \\ & K \to l\nu & \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \pi l\nu & D \to K l\nu & B \to D^{(*)} l\nu \\ D \to l\nu & D_s \to l\nu & \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ \langle B_d | \overline{B}_d \rangle & \langle B_s | \overline{B}_s \rangle & \end{pmatrix}$$

Kaon Decay Constant





F_K/F_π Summary



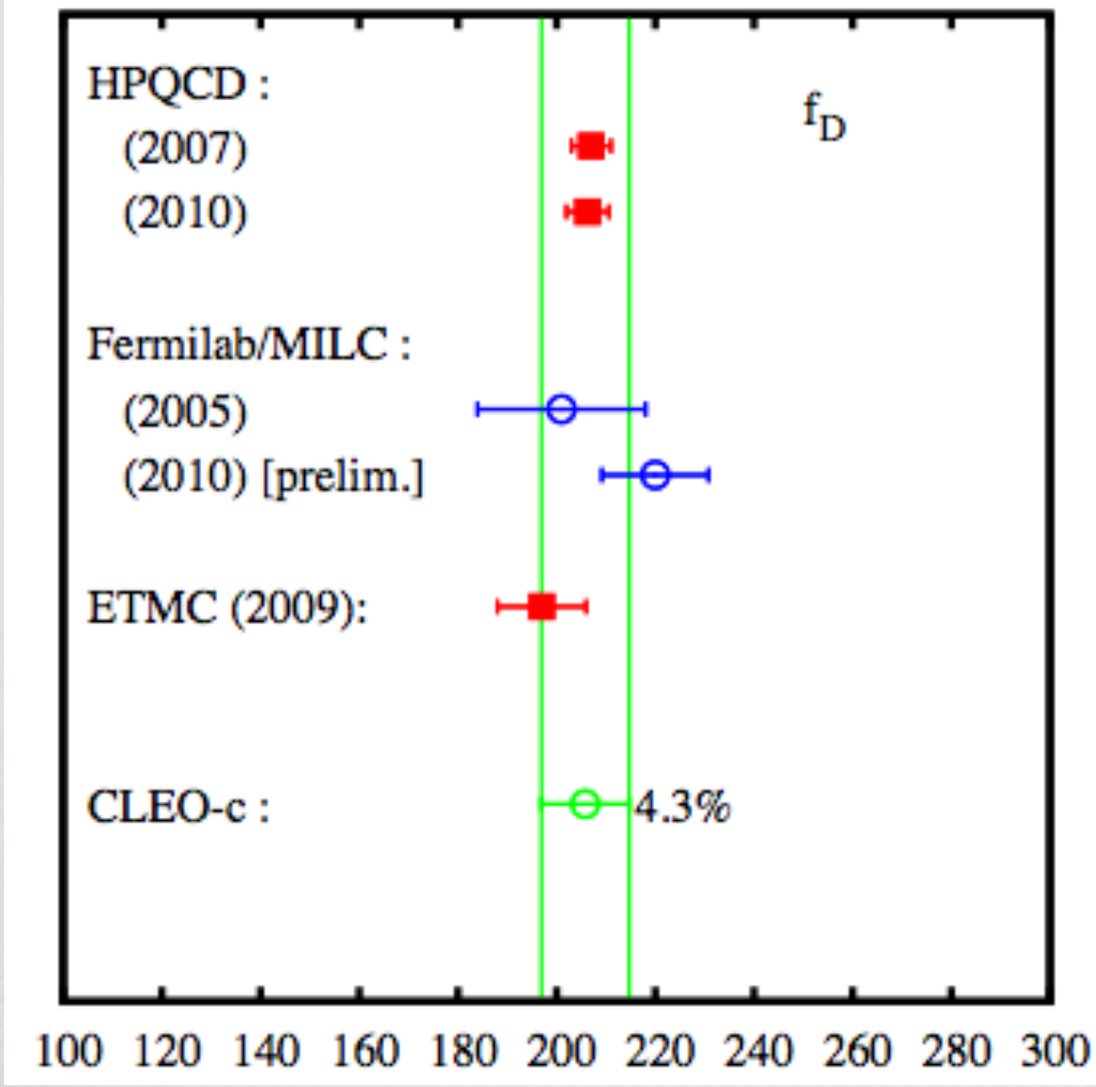
- ratio of f_K to f_π can be used to extract V_{us} (Marciano)
- results below MILC (Lattice10) preliminary (Bernard talk)
- world averages:
  - FlaviaNet: 1.193(6)
  - LLV: 1.1925(56)

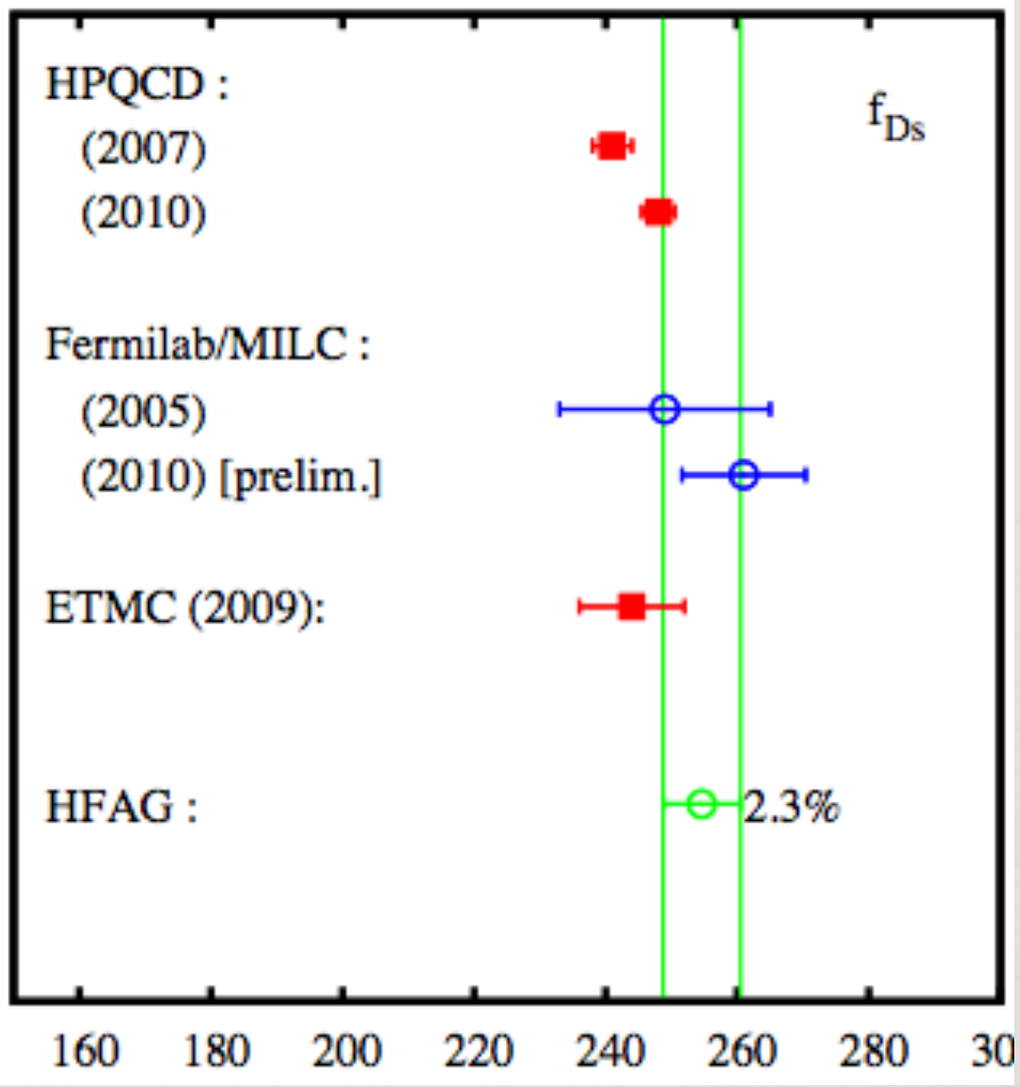
$$f_K = 156.1 \pm 0.4 \left(^{+0.6}_{-0.9}\right) \text{ MeV}$$
$$f_K/f_\pi = 1.197(2) \left(^{+3}_{-7}\right)$$
$$V_{us} = 0.2247 \left(^{+14}_{-9}\right)$$

Charm, Bottom Decay Constants

- Lattice calculations of charm decay constants can be tested by experiment.
- Initial results of FNAL/MILC's calculations were considered a successful prediction of lattice QCD, when tested by CLEO-c.
- Both experimentalists and theorists have worked to improve precision of comparison.
- Situation got very interesting for f_{Ds} a few years ago...
  - no smoking gun for new physics now

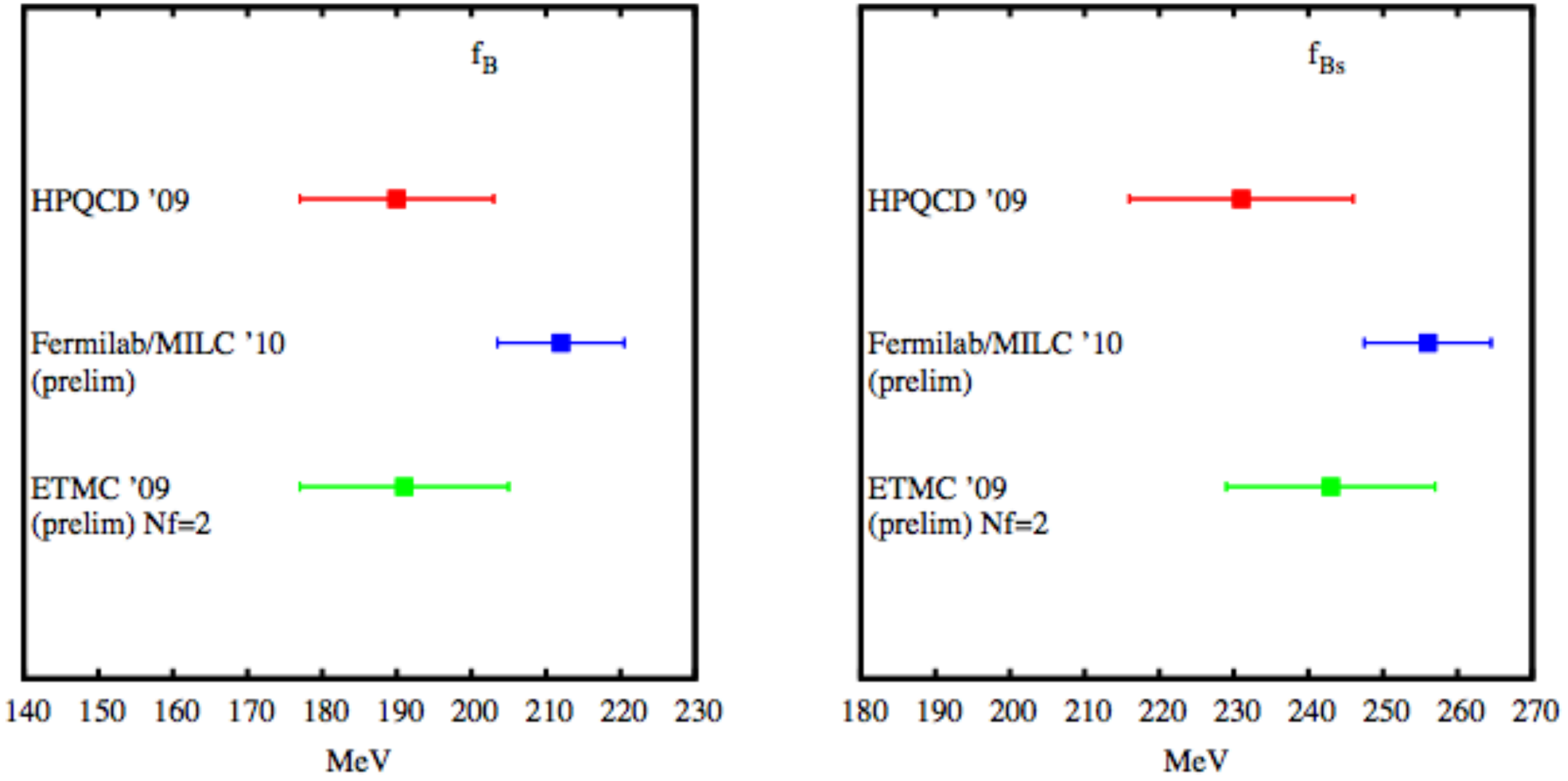
summary plot from Shigemitsu CKM2010





- ETMC result is for N_f=2, but N_f=2+1+1 is coming

summary plot from Shigemitsu CKM2010



- ETMC result is for N_f=2, but N_f=2+1+1 is coming
- No experimental comparison

D semileptonic decays

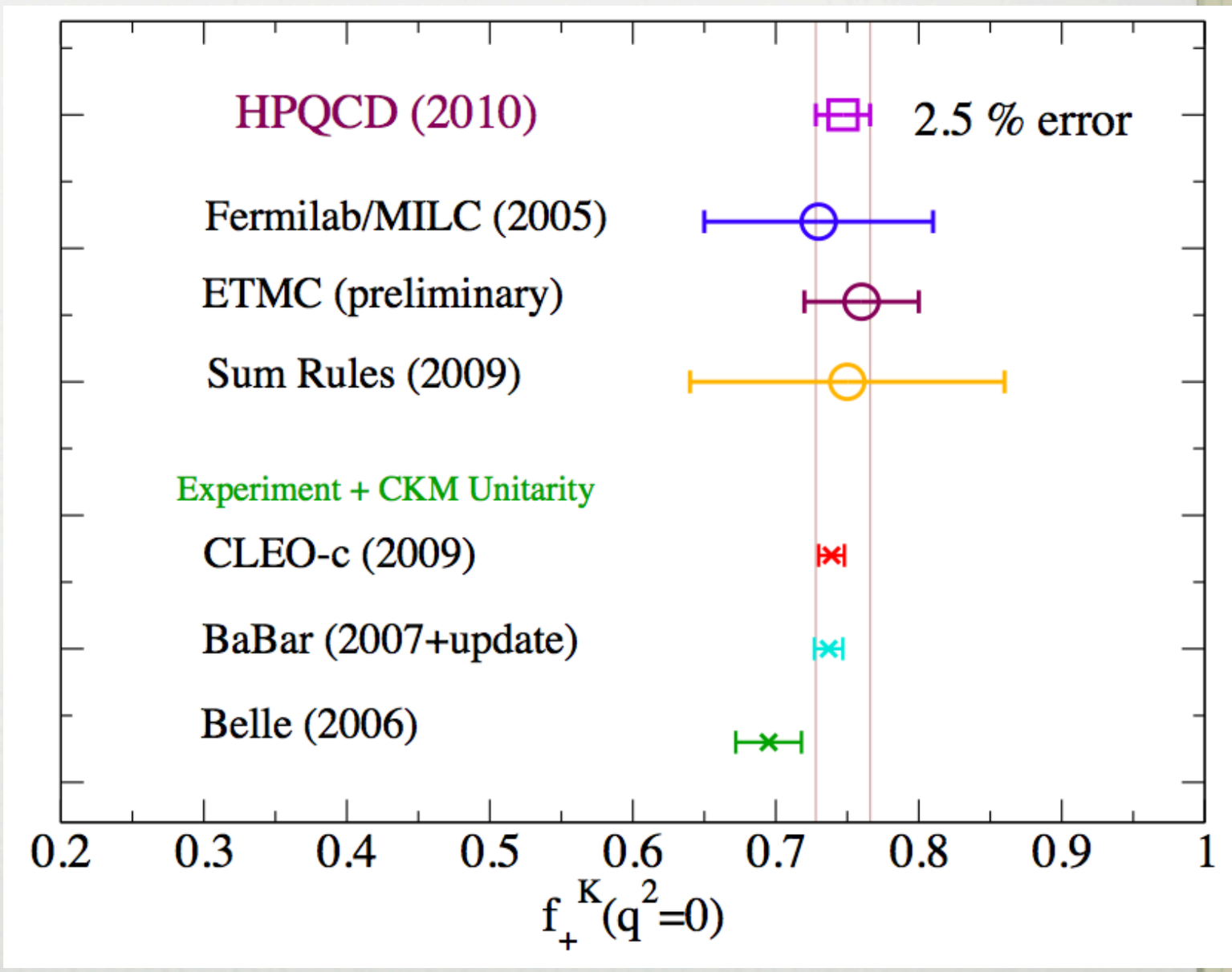
- D semileptonic decay to K and π plus lv are both under active study

- HPQCD has recently improved result for K final state

- Reviewed by Heechang Na at CKM 2010. Also see talk at Lattice 2010.

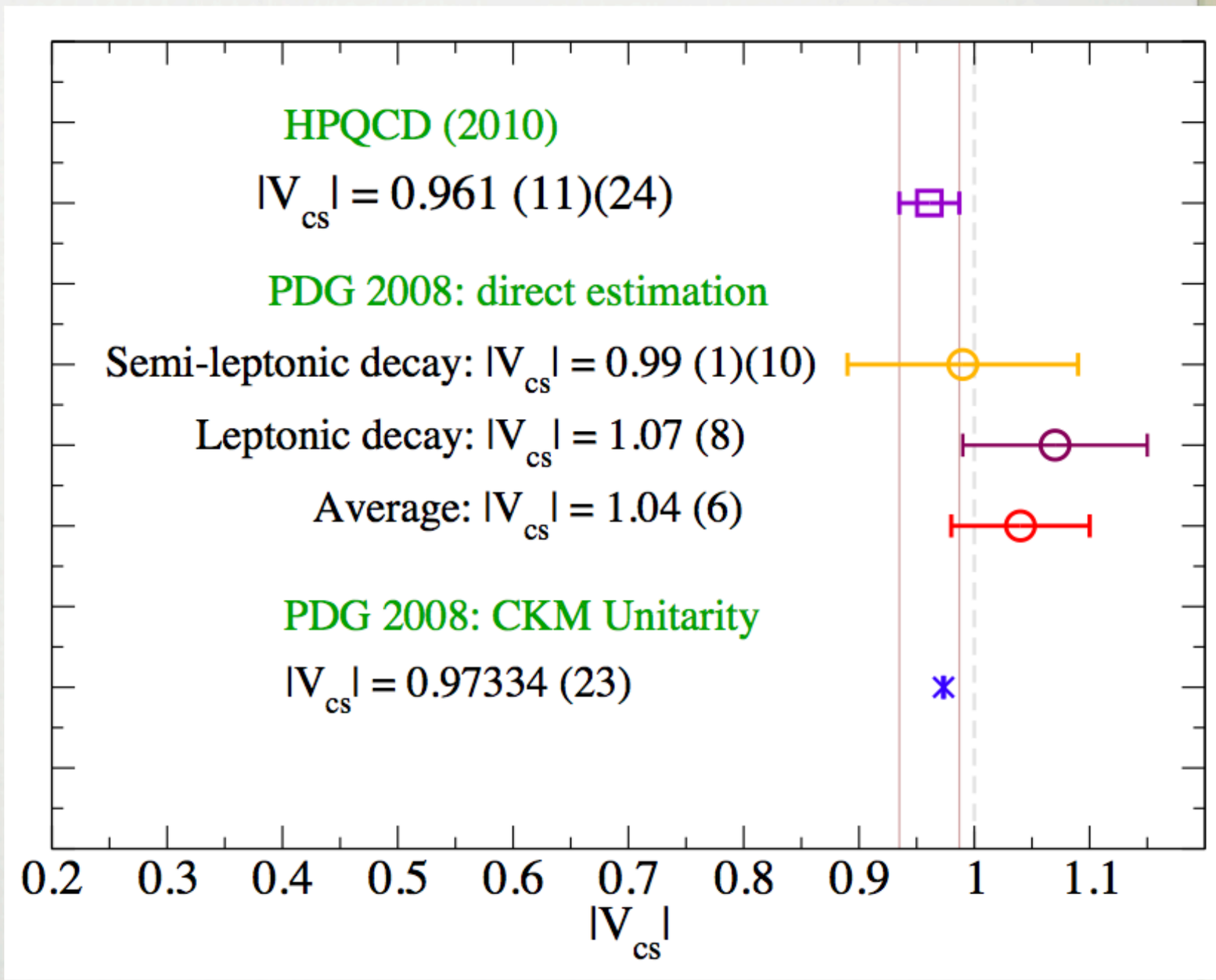
$f_+^K (q^2=0)$

- Several improvements have allowed a greatly reduced error by HPQCD.
- Nice agreement with experiment assuming CKM unitarity.
- From Na at CKM2010



$|V_{cs}|$

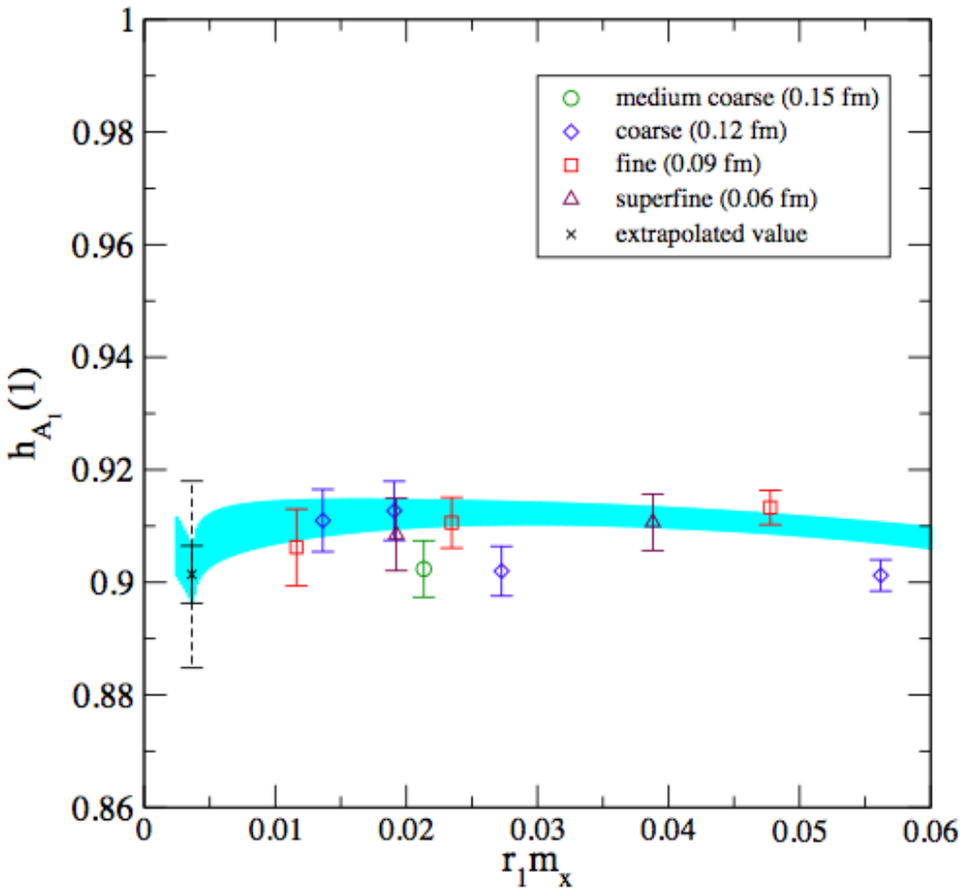
- Here Na (CKKM2010) displays value of $|V_{cs}|$
- Value is in good agreement with assumption of CKM unitarity
- Clearly error much improved. Previously about 10%.



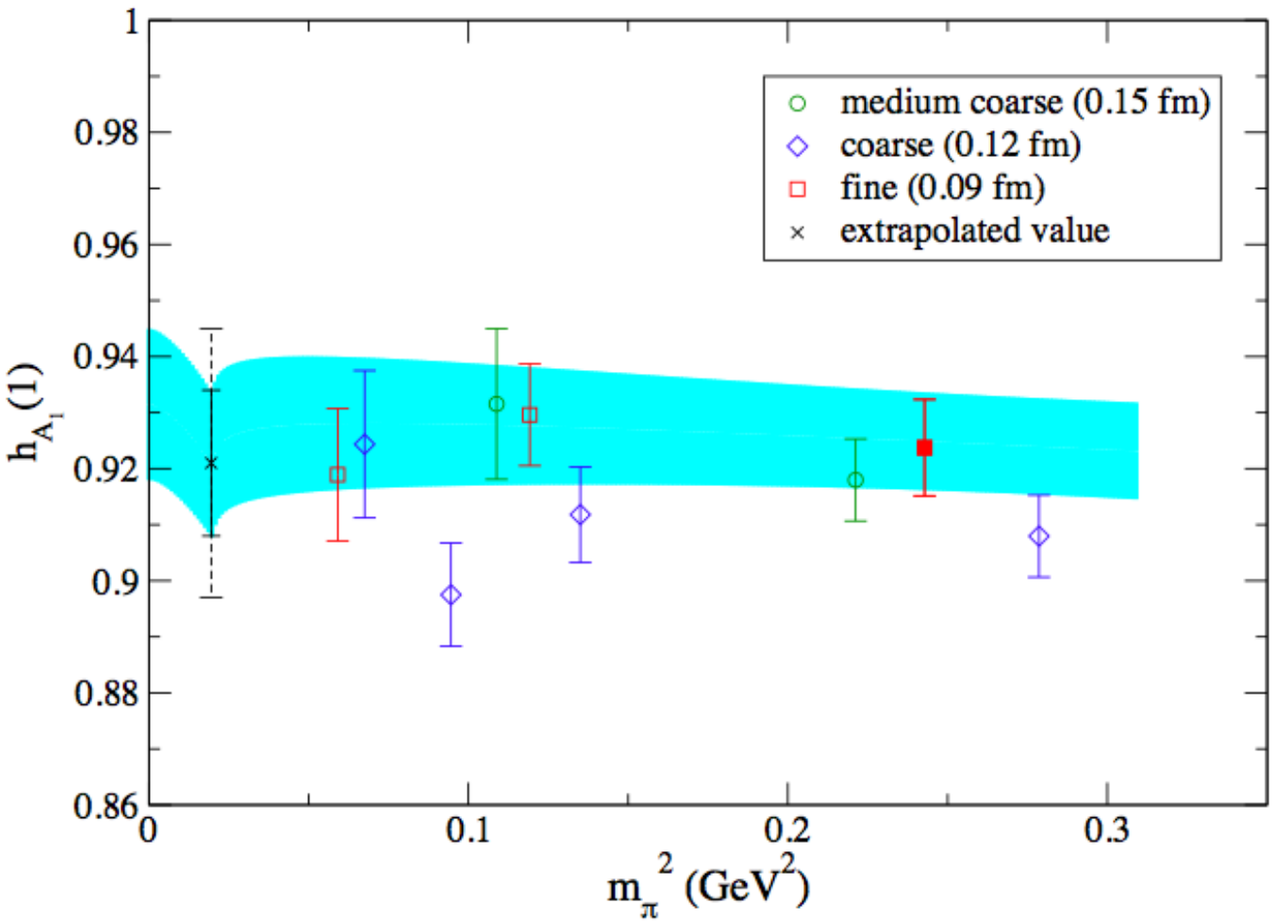
$B \Rightarrow D^* l \nu$

2010

χ^2/dof = 8.9/12, CL=0.72



Compare 2008



- FNAL/MILC result presented by Mackenzie at CKM2010

- Improved statistics and kappa tuning result in an improved value for $|V_{cb}|$. (first error is from expt, second from lattice calculation)
  - 2008: 38.9(7)(1.0) 10^{-3}
  - 2010: 39.7(7)(7) 10^{-3}
- Value from inclusive decays is 41.7(7) 10^{-3} .
- Difference between two determinations reduced from 2.6 σ to 1.6 σ.
- Further reduction of error is expected with additional ensembles.

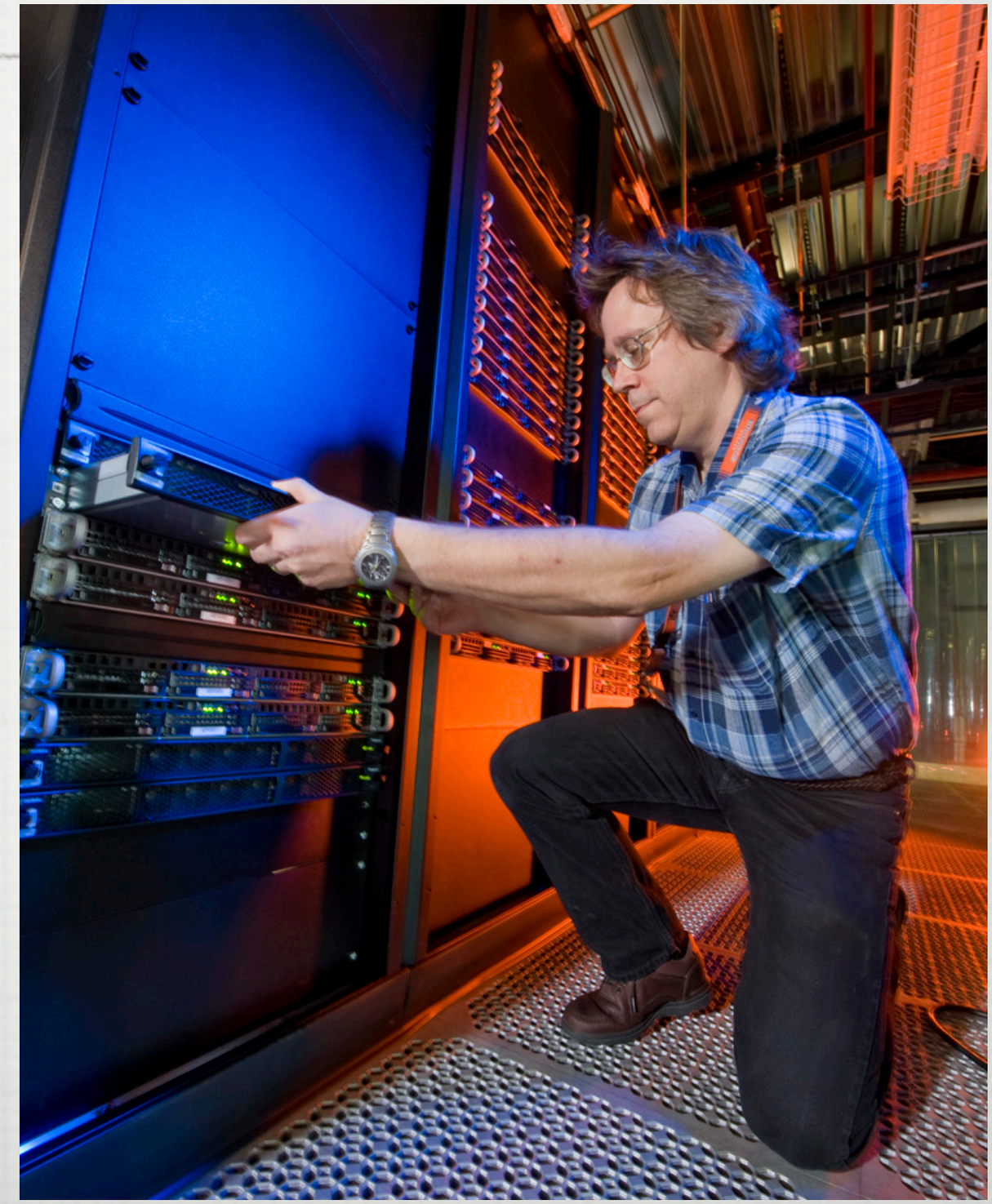
Computing

USQCD

- Lattice QCD Computing Project
  - BNL: QCDOC, BlueGene Q(?)
  - FNAL, JLab: clusters, GPUs
- A New Kind of User
  - Approximately 100 scientists have logins at the three labs
- INCITE: ALCF (Intrepid, Mira); ONRL (Jaguar, Kraken)

FNAL

- Kaon: 2400 cores; DDR Infiniband
- J/ψ: 6848 cores; DDR Infiniband
- Ds: 7840+5632 cores; QCD Infiniband
- GPU: 128 GPUs (coming soon)

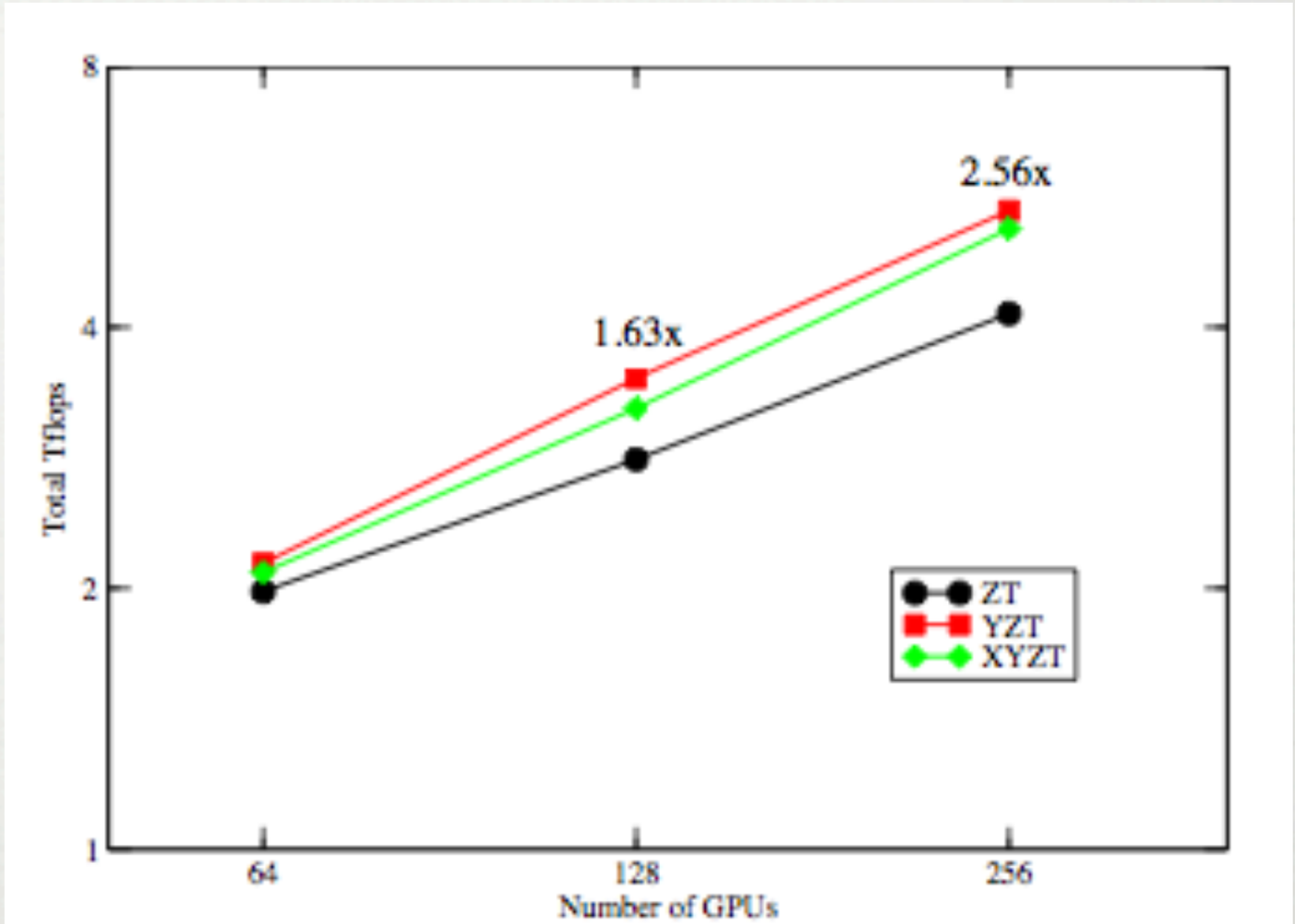


GPU computing

- Need many parallel threads (10Ks); little branching
- Very unbalanced architecture:
  - high bandwidth to GPU memory (150 GB/s); but not compared to FP power (500-1000 GF/s)
  - internode communication is slow because of extra hops, but should improve in future (GPU Direct)
- QUDA software designed for QCD can partition lattice by cutting in all 4 directions enabling scaling to O(100) GPUs

Scaling with Staggered Quarks

- 64^3 X 192 lattice
- Mixed precision multi-mass solver
- Achieving over 4 TFlops on 256 GPUs



Thank You!